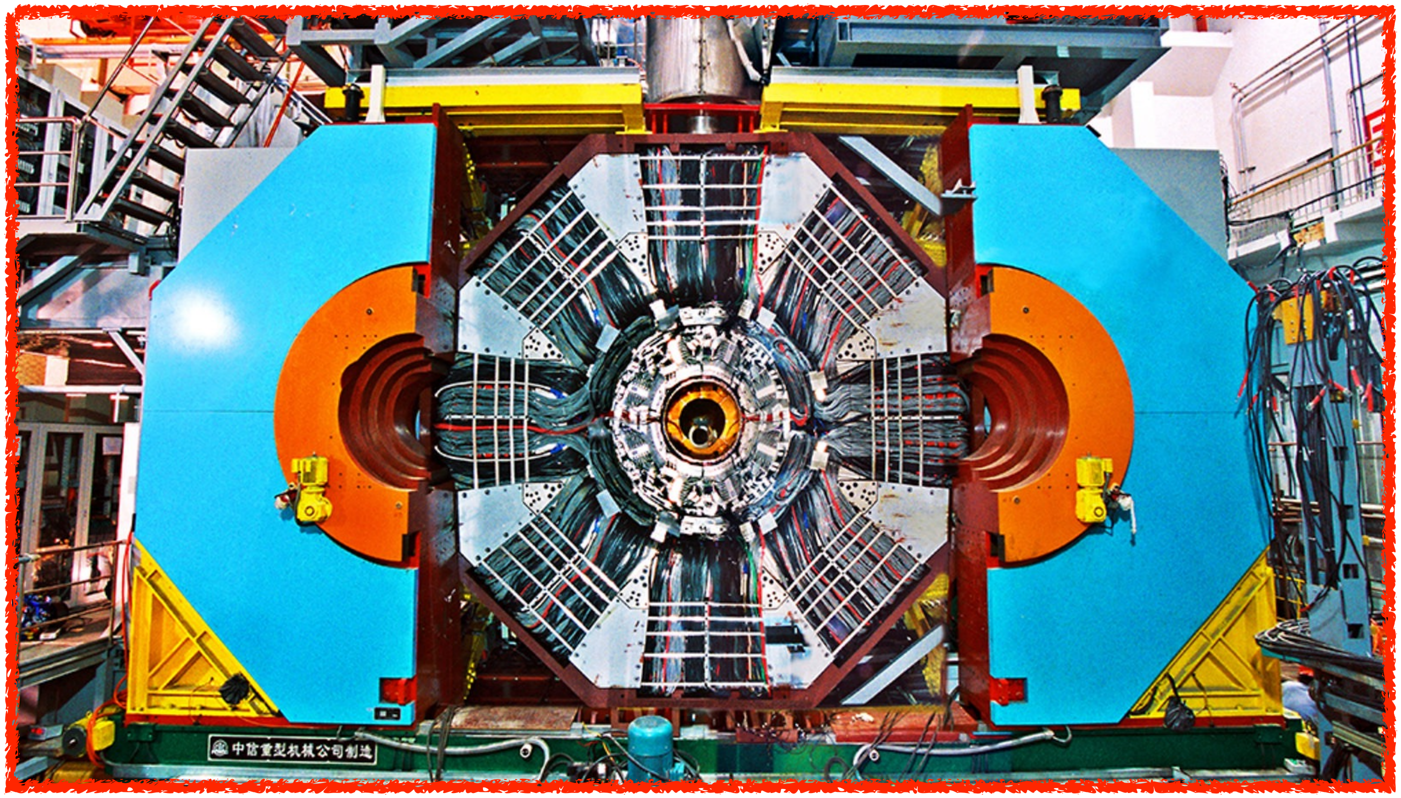
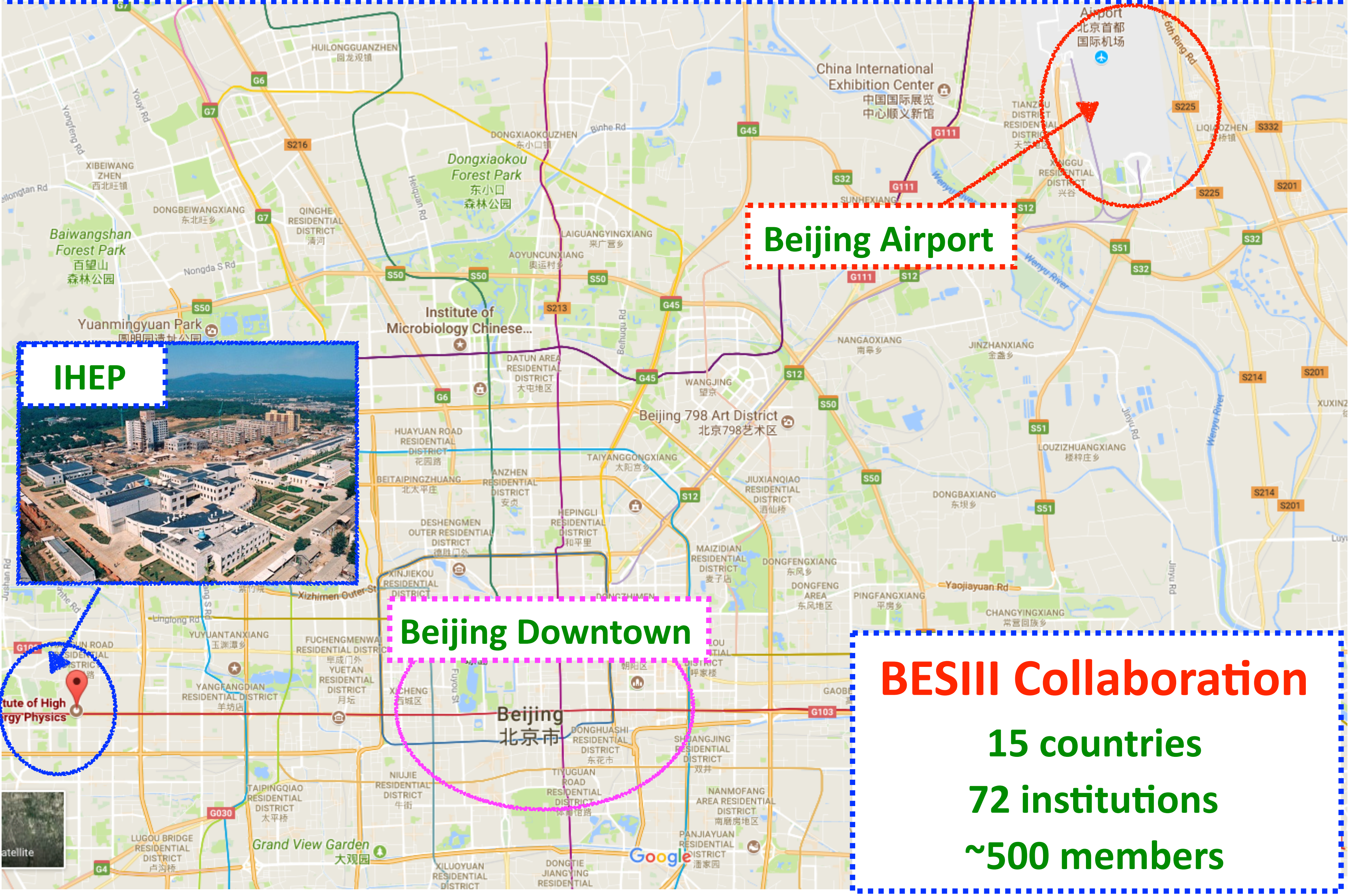
Selected recent results in hadronic charm decays at BESIII



Hajime Muramatsu
University of Minnesota

BESIII is at Institute of High Energy Physics (IHEP) in Beijing, China



IHEP

Beijing Airport

Beijing Downtown

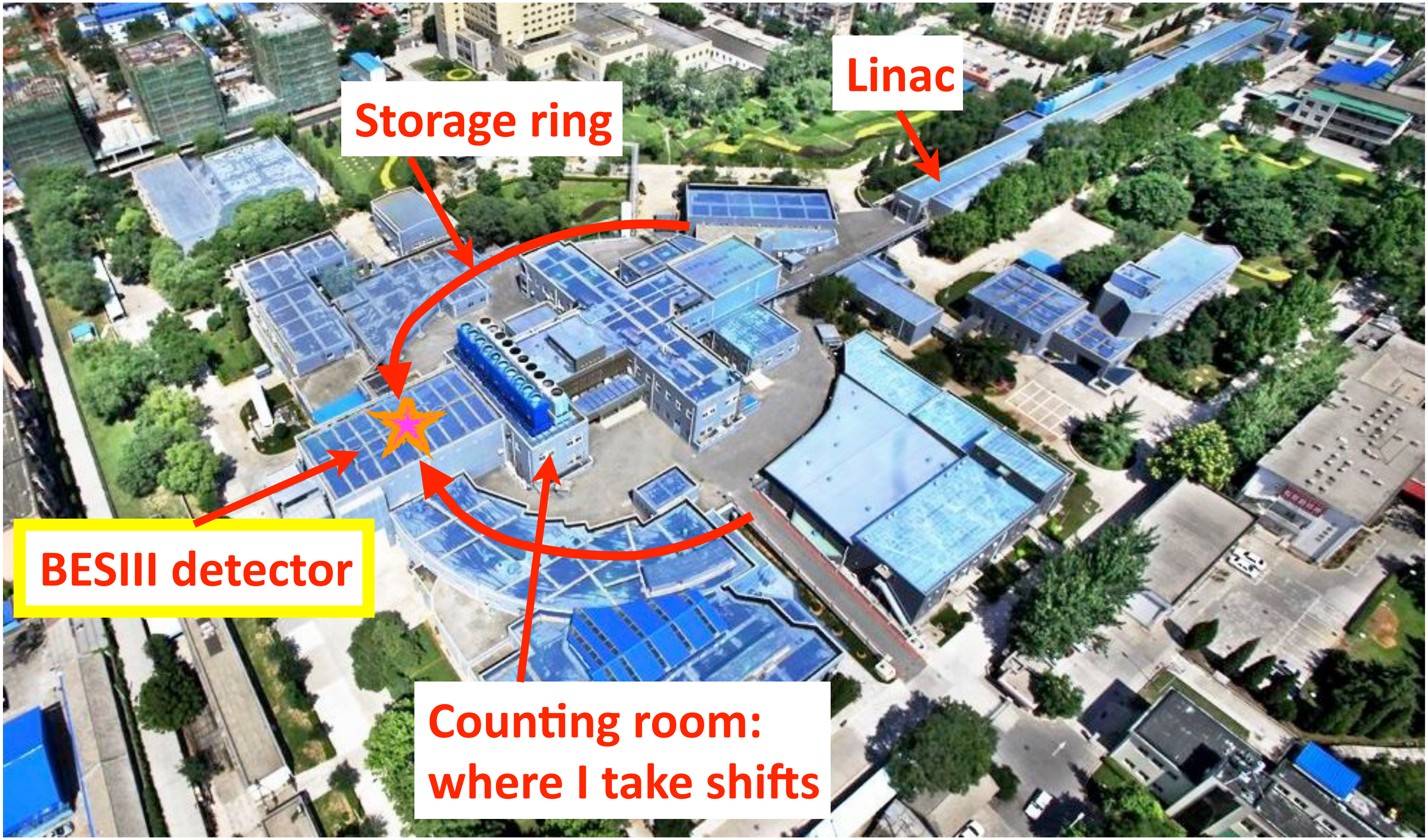
BESIII Collaboration

15 countries

72 institutions

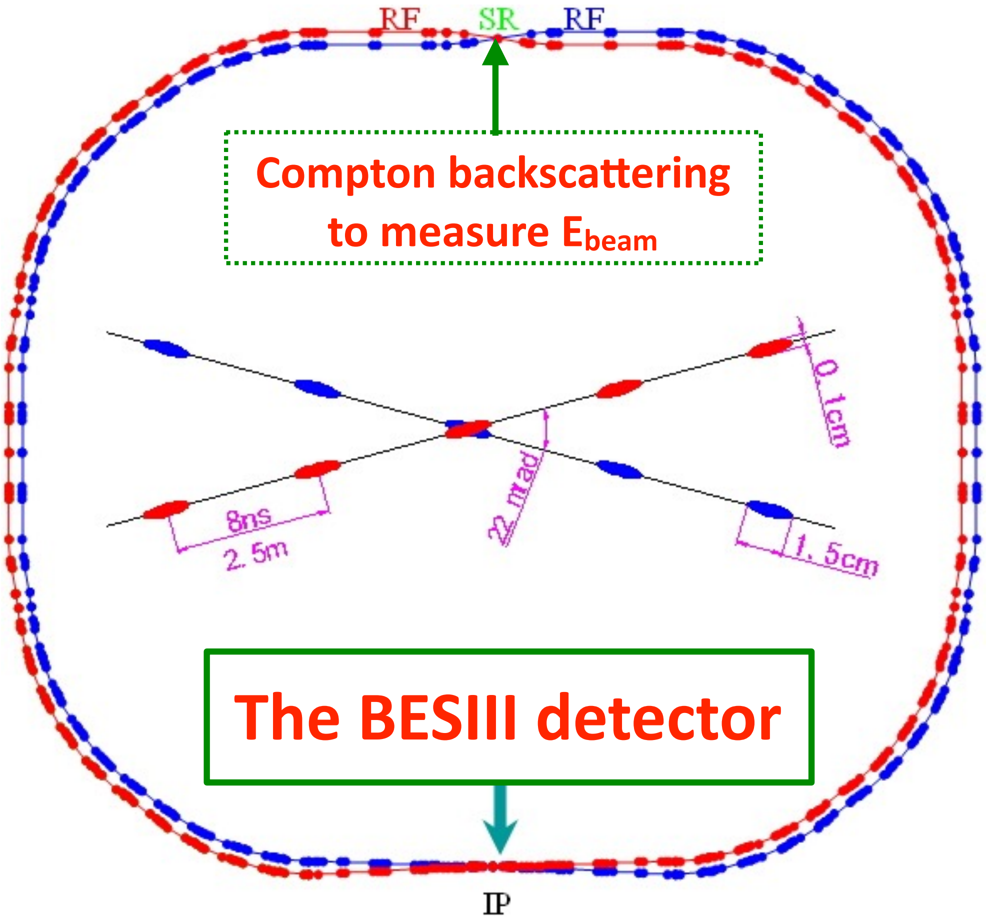
~500 members

BEPC II and BESIII



BEPC II
(Beijing Electron-Positron Collider II)

- Double ring collider.
- Operating since 2008.
- E_{beam} = 1-2.3 GeV.
  Optimal @ 1.89 GeV.



Compton backscattering to measure E_{beam}

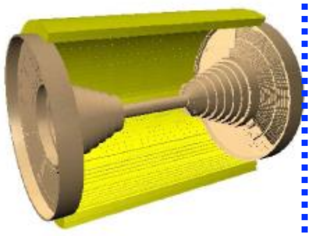
The BESIII detector

- Can fill up to 93 bunches in each ring w/ max current of 0.9A.
- Designed luminosity = 1×10^{33} $cm^{-2}s^{-1}$ was achieved in April 2016!

BESIII detector

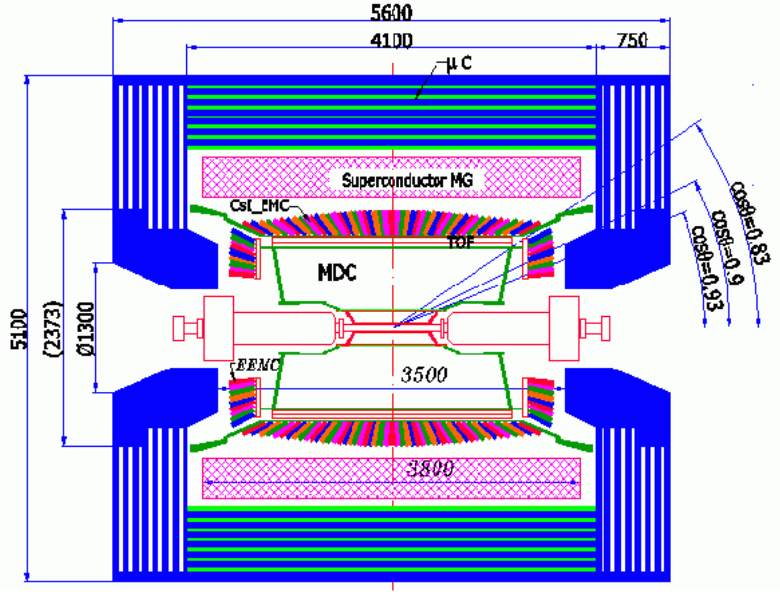
- A powerful general purpose detector.
- Excellent neutral/charged particle detection/identification with a large coverage.
  - ✓ Precision tracking
  - ✓ CsI calorimeter
  - ✓ PID via dE/dx & Time of Flight

MDC: small cell & Gas:
He/C_3H_8 (60/40), 43 layers
$\sigma_p/p=0.5\%$@1GeV, $\sigma_{dEdx}=6\%$

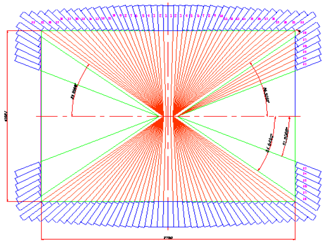


R inner: 63mm ;
R outer: 810mm
Length: 2582 mm
Layers: 43

Magnet: 1T Super conducting

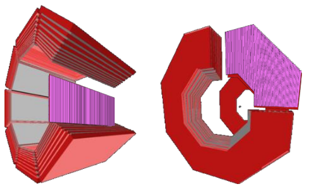


EMCAL: CsI(Tl) crystal
ΔE/E=2.5 @1GeV



Crystals: 28 cm(15 X_0)
Barrel: $|\cos\theta|<0.83$
Endcap:
$0.85 < |\cos\theta| < 0.93$

MUC: 9 layers RPC
(8 layers in Endcap)
$\sigma_{R\Phi}$=1.4~1.7cm



Time of Flight
σ_T=100ps in Barrel
110ps in Endcap

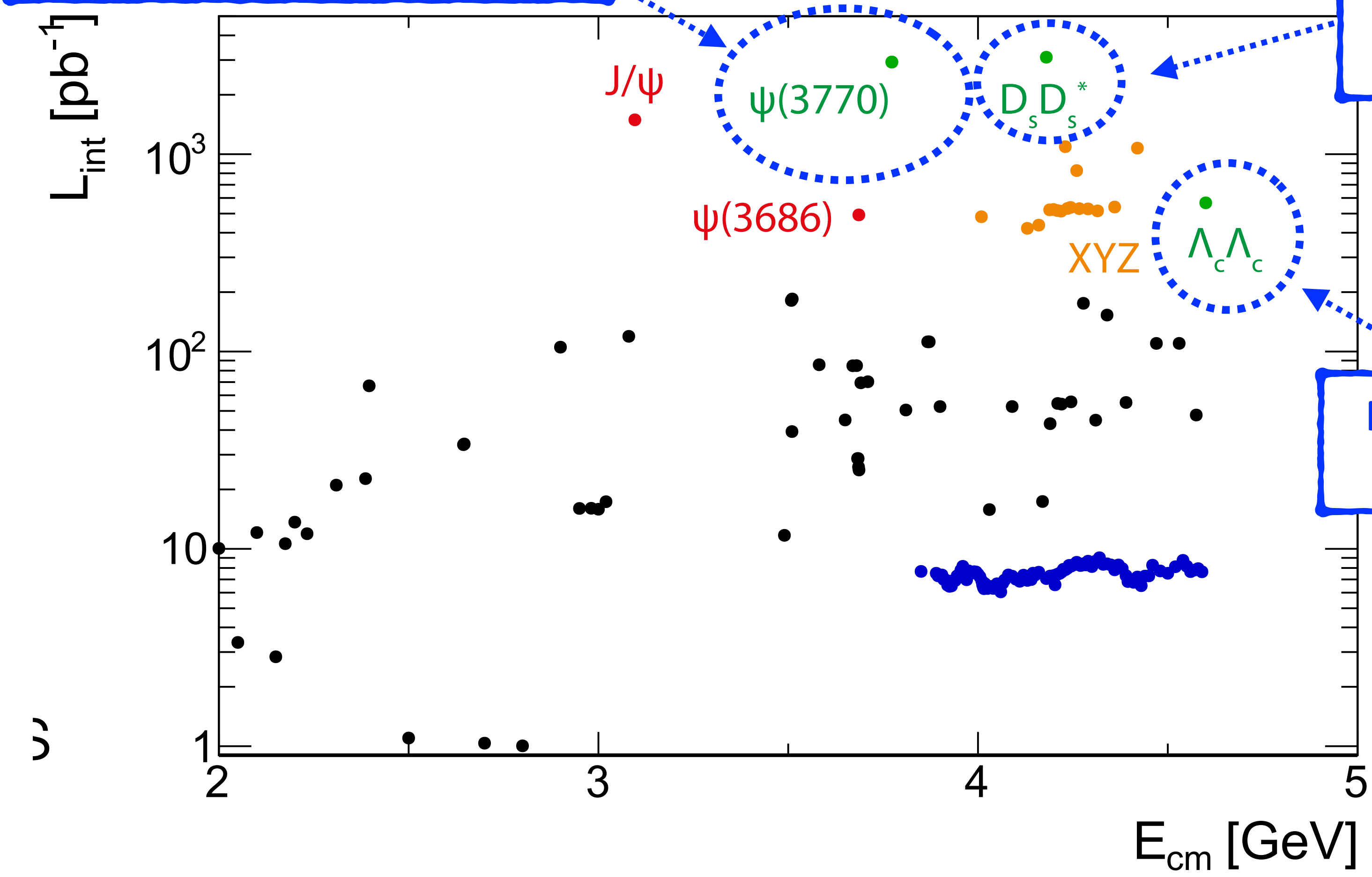
BTOF: two layers
ETOF: 48 scintillators for each
MRPC --- new ETOF

e^+e^- annihilation samples taken E_{cm} from ~2 GeV up to ~4.6 GeV

N_{D0D0} = $(10{,}597 \pm 28 \pm 98) \times 10^3$
N_{D+D-} = $(8{,}296 \pm 31 \pm 65) \times 10^3$
produced

$\sqrt{s}$ / GeV	$\mathcal{L}$ / fb^{-1}	
3.77	2.93	$D\bar{D}$
4.008	0.48	DD^*, $\psi(4040)$, $D_s^+D_s^-$
4.18	3.2	$D_sD_s^*$
4.6	0.59	$\Lambda_c^+\bar{\Lambda}_c^-$

N_{Ds^*Ds} ~ 3M produced



$N_{\Lambda c\bar{\Lambda}c}$ = $(105.9 \pm 4.8 \pm 0.5) \times 10^3$
produced

Typical analysis method to measure BF

- In our sample, $D_{(s)}$ mesons (and Λ_c) are produced in pair:
  @ E_{cm} = 3773 MeV : $e^+e^- \rightarrow D\bar{D}$
  @ E_{cm} = 4178 MeV : $e^+e^- \rightarrow D_s^* D_s$ (subsequently $D_s^* \rightarrow (\gamma/\pi^0)\, D_s$)
  @ E_{cm} = 4600 MeV : $e^+e^- \rightarrow \Lambda_c \bar{\Lambda}_c$.

- Reconstruct one of the $D_{(s)}$ (tag),
  you know there must be the other $D_{(s)}$ (signal),
  allowing measurements of absolute BFs,
  without the knowledge of data size or N_D produced.

I.e., $BF(D_s \rightarrow KK\pi) = [B(D_s \rightarrow tag) \times BF(D_s \rightarrow KK\pi)]/BF(D_s \rightarrow tag)$
= [Double Tag yields]/[Single Tag yields].

Systematics associated with the reconstruction of $D_s \rightarrow$ tag also tend to be canceled in this ratio.

Or one could solve for N_D produced

- In $e^+e^- \to D\bar{D}$ events, where $D \to X$ and $\bar{D} \to Y$,
  let $BF(D \to X) = N_x/(\varepsilon_x \cdot N_{D\bar{D}})$: Single Tag (ST)
  $BF(\bar{D} \to Y) = N_y/(\varepsilon_y \cdot N_{D\bar{D}})$: Single Tag (ST)
  $BF(D \to X) \times BF(\bar{D} \to Y) = N_{xy}/(\varepsilon_{xy} \cdot N_{D\bar{D}})$: Double Tag (DT)
  Solving for the common factor,
  $$N_{D\bar{D}} = [N_x \cdot N_y/N_{xy}] \times [\varepsilon_{xy}/(\varepsilon_x \cdot \varepsilon_y)].$$
  The resultant $N_{D\bar{D}}$ can be used to normalize signal yields, where only single D is reconstructed (useful method when statistically limited), to obtain an absolute BF.

- Or with the measured integrated luminosity at E_{cm} = 3773 MeV,
  $L = 2920\ fb^{-1}$ (Chin.Phys.C37, 123001 (2013)),
  an observed cross section is readily obtained:
  $$\sigma = N_{D\bar{D}}/L.$$

Published in Chinese Physics C 42, 083001 (2018)

$\sigma(e^+e^- \rightarrow D\bar{D})$ at E_{cm} = 3.773 GeV

- Such analysis was published in CPC, which allows author names printed in Chinese characters!

毛泽普)[1], S. Marcello[55A,55C], Z. X. Meng(孟召霞
Min(闵天觉)[1], R. E. Mitchell[21], X. H. Mo(莫晓虎
Muchnoi[9,d], H. Muramatsu(村松創)[49], A. Musta
(宁哲)[1,42], S. Nisar[8], S. L. Niu(牛顺利)[1,42], X. Y.
, Y. Pan(潘越)[42,52], M. Papenbrock[56], P. Patter

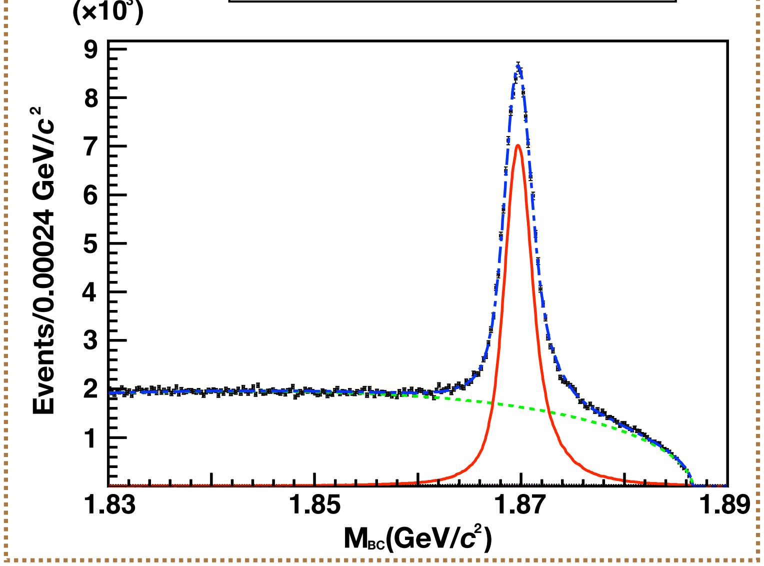
- In this analysis, N_x and N_y are extracted by fitting to M_{BC} (with cut on ΔE)
- Extract N_{xy} by fitting to a 2D; M_{BC}^y v.s. M_{BC}^x .
- Two popular variables:
  - Beam-Constrained-Mass; $M_{BC} = \sqrt{(E_{beam}^2 - |\vec{p}_D|^2)}$

    $\vec{p}_D$ is a reconstructed D 3-momentum.

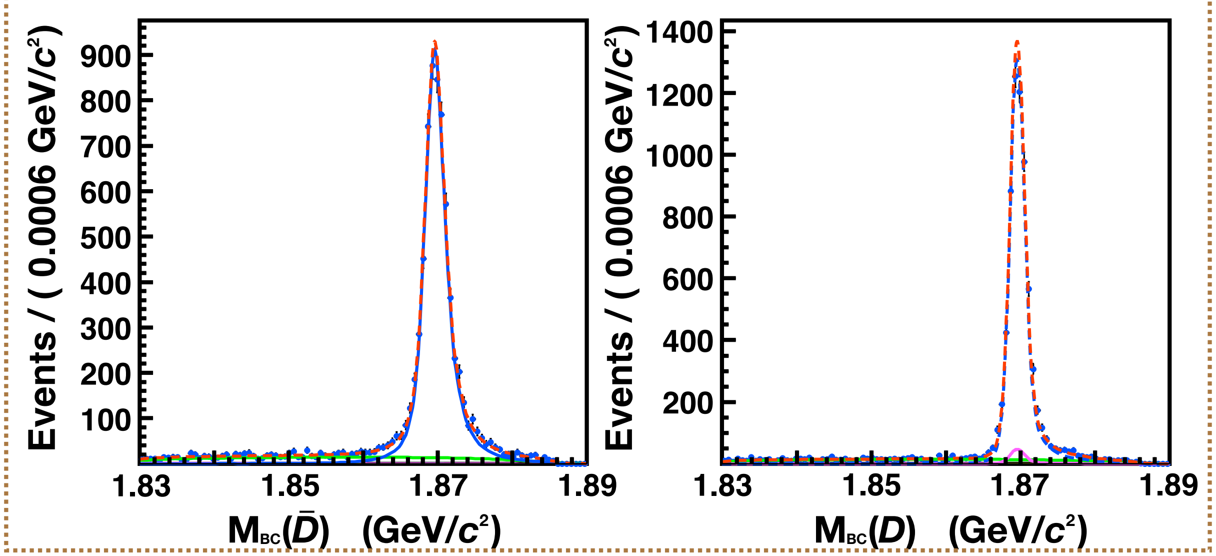
    - Its resolution is typically dominated by the spread in E_{beam} (i.e., independent of final states of D).
  - $\Delta E = E_D - E_{beam}$
    - Almost independent of the measured M_{BC}.

$\sigma(e^+e^- \rightarrow D\bar{D})$ at E_{cm} = 3.773 GeV

ST: $D^+ \rightarrow K^-\pi^+\pi^+\pi^0$



DT: $D^+ \rightarrow K^-\pi^+\pi^+\pi^0$ and $D^- \rightarrow K^+\pi^-\pi^-$



- Averaging the resultant cross sections over different decay modes (X and Y), we have;

  $\sigma(e^+e^- \rightarrow D^0\bar{D}^0)$ = 3.615±0.010 (stat.)±0.038 nb

  $\sigma(e^+e^- \rightarrow D^+D^-)$ = 2.830±0.011 (stat.)±0.026 nb.

  And

  N_{D0D0} = (10,597±28±98)×10^3

  N_{D+D-} = (8,296±31±65)×10^3.

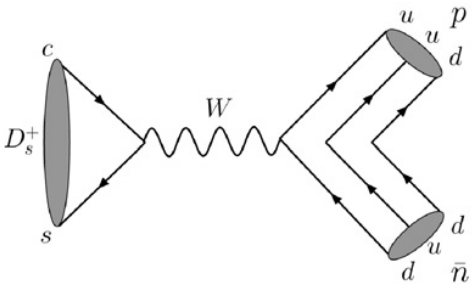
Today, I report some of our resent results in:

- Two body decays of D and D_s.
- Three body decays of D and D_s.
- Λ_c decays.

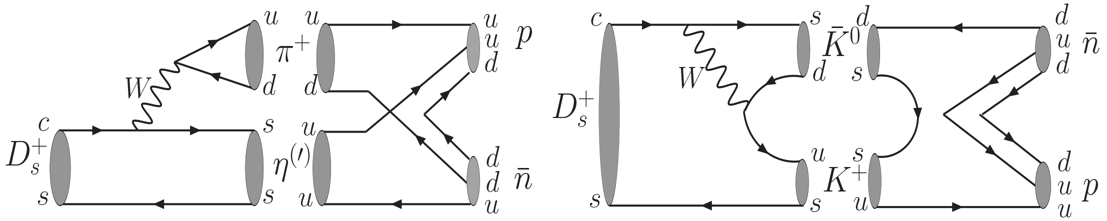
Two-body decays

$D_s \to p\,\bar{n}$
based on the 4178 data

- The only kinematically allowed hadronic decay, involving baryons.
- Short-distance contribution is expected to be small : BF ~ 10^{-6} due to the chiral suppression by a factor of $(m_\pi/m_{D_s})^4$.



But long-distance can enhance BF to ~10^{-3} (C.H. Chen, et al. PLB663, 326).



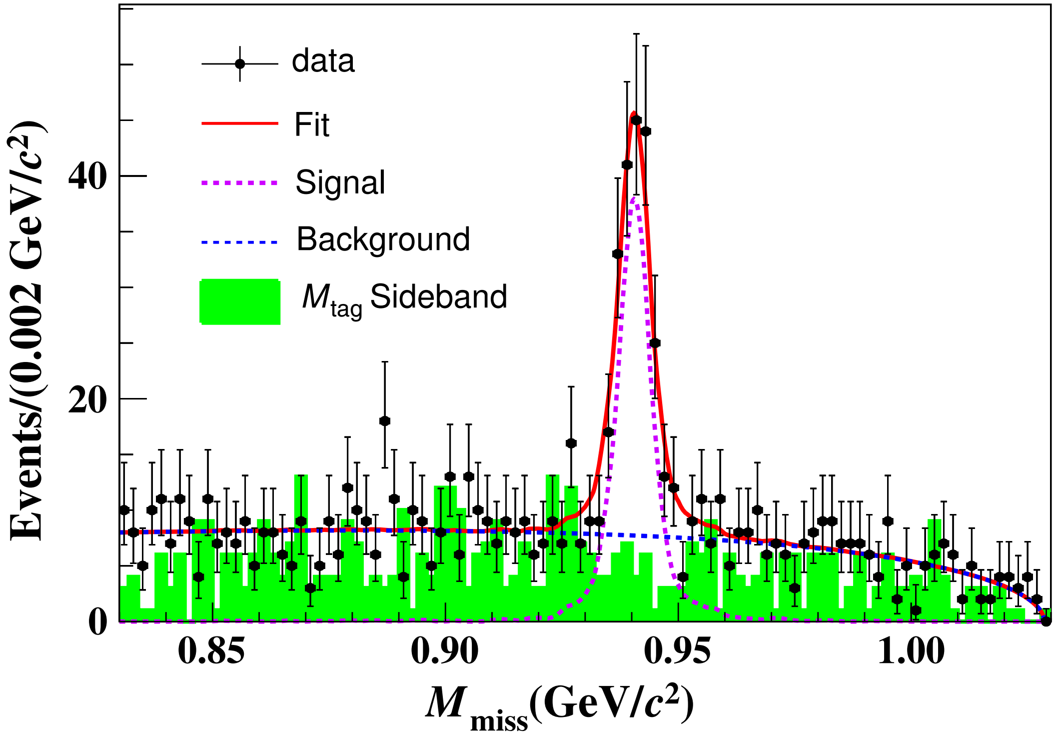
- First evidence was reported by CLEO with a signal of 13.0±3.6 events with BF = $(1.30\pm0.36^{+0.12}_{-0.16})\times10^{-3}$ (PRL100, 181802).

Published in PRD99, 031101(R) (2019)

$D_s \rightarrow p\,\bar{n}$ based on the 4178 data

- DT: Reconstruct all final states, except the neutron: M_{miss} = missing mass = $M_{neutron}$.

- BESIII confirms it is indeed large: BF = $(1.21\pm0.10\pm0.05)\times10^{-3}$.



- The short distance dynamics is not the driven mechanism. The hadronization process, driven by nonperturbative dynamics determines the underlying physics.

$D_s \to \omega\pi$ and ωK based on the 4178 data

- $\omega\pi$: CF : Has seen by CLEO (PRD80,051102) : BF = $(2.1\pm0.9\pm0.1)\times10^{-3}$.
- ωK: SCS: CLEO (PRD80,051102) set an UL = 2.4×10^{-3} @ 90% C.L.

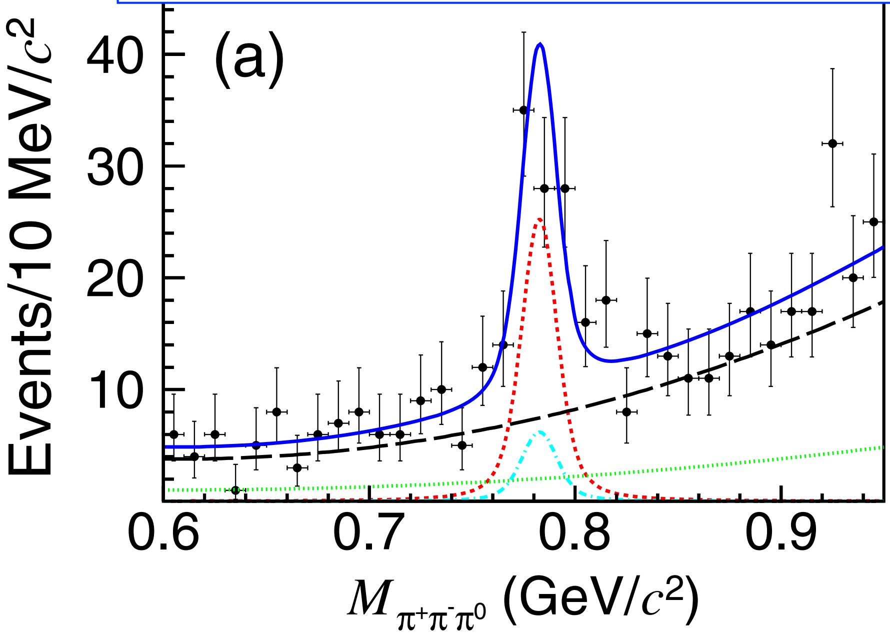
- Q. Qin et al. (PRD89, 054006) predicts (factorization)
  BF(ωK) ~ 0.6×10^{-3} (with A_{cp} ~ -0.6×10^{-3}) or
  it could become ~0.07×10^{-4} (with A_{cp} ~ -2.3×10^{-3})
  if ρ-ω mixing is considered.

- DT method: Reconstruct the all final states.
- Cut on $\Delta M = M_{signal\text{-}side} - M_{tag\text{-}side}$ to select $D_s \to$ tag and and the other $D_s \to \omega\ (\pi/K)$.
- Then project onto $M_{\pi\pi\pi0}$.

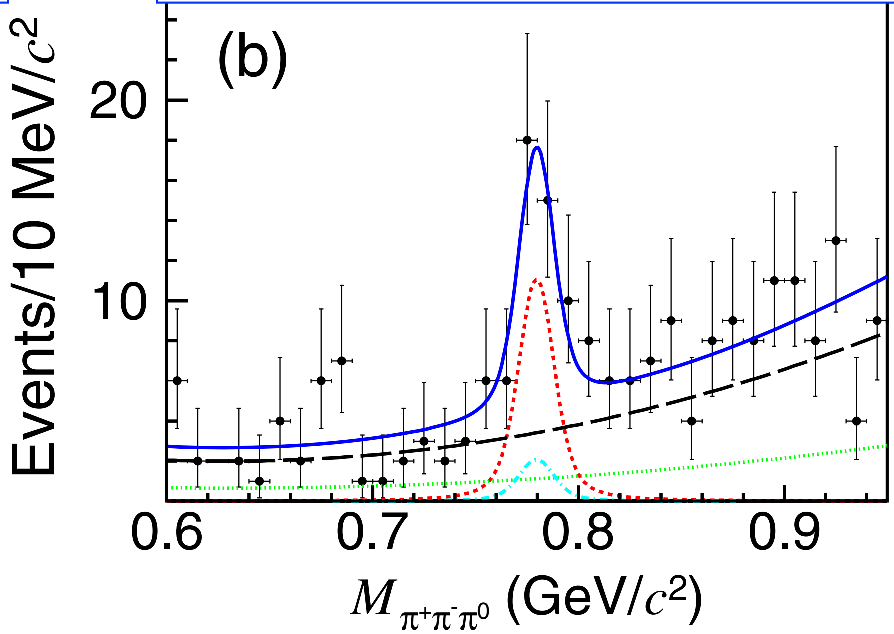
Published in PRD 99, 091101 (R) (2019)

Projecting onto $M_{\pi\pi\pi0}$ from the signal region of ΔM

ωπ:65.0±11.6 evts (6.7σ)



ωK:28.5±7.8 evts (4.4σ)

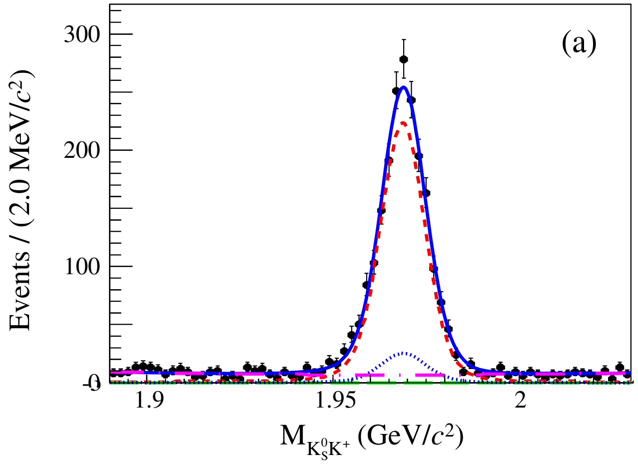


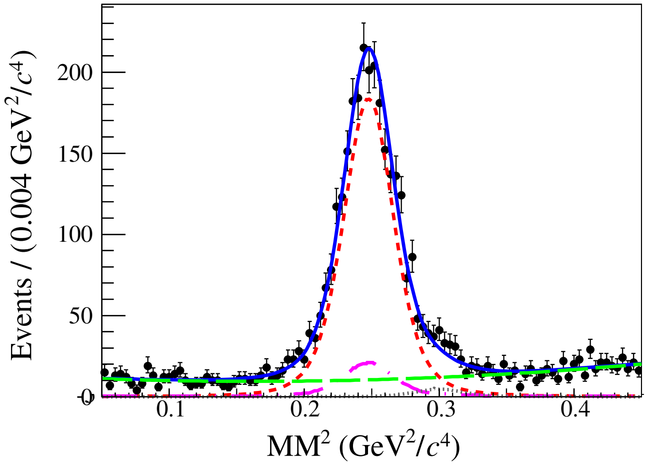
- BF(D_s → ωπ) = $(1.77\pm0.32\pm0.13)\times10^{-3}$
  Consistent with CLEO's measurement, but more precise.
- BF(D_s → ωK) = $(0.87\pm0.24\pm0.08)\times10^{-3}$:First evidence!
  According to Qin et al., this implies $A_{cp} \sim -0.6\times10^{-3}$. and negligible effect from ρ-ω mixing.

Published in PRD 99, 112005 (2019)

$D_s \to K_S K$ and $K_L K$ based on the 4178 data

- As in $D \to K^0\pi$ and $D \to \bar{K}^0\pi$ could interfere, so can the CF and DCS amplitudes in D_s decays : $D_s^+ \to K^0K^+$ and $D_s^+ \to \bar{K}^0K^+$.
- Such interference effect could also lead to CPV : $A_{CP} \sim 10^{-3}$, predicted by D. Wang et al. (PRL 119, 181802 (2017)).



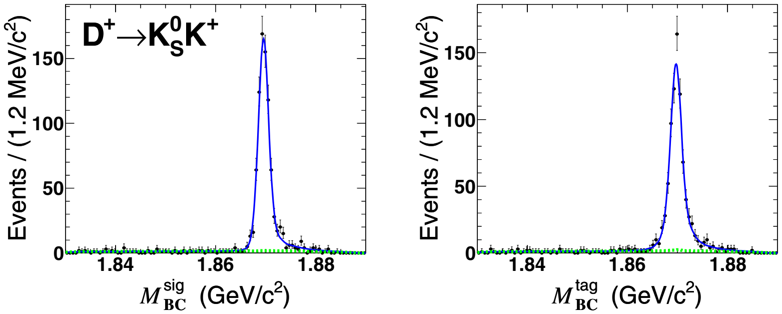


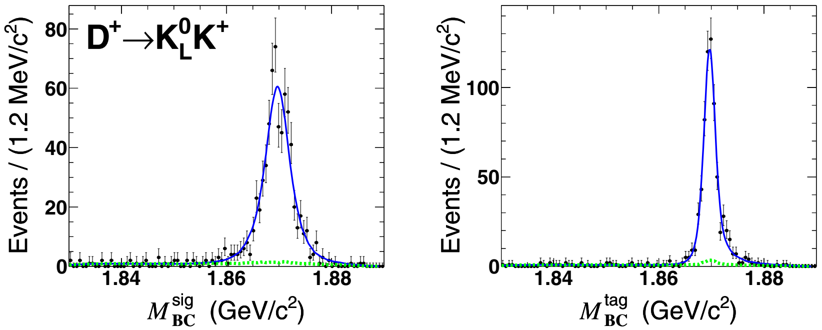
- BF($D_s^+ \to K_S K^+$) = (1.425±0.038±0.031)%, consistent with the WA.
- BF($D_s^+ \to K_L K^+$) = (1.485±0.039±0.046)%, 1st measurement.
- K_S/K_L asymmetry, R = $\frac{\mathcal{B}(D_s^+\to K_S^0K^+)-\mathcal{B}(D_s^+\to K_L^0K^+)}{\mathcal{B}(D_s^+\to K_S^0K^+)+\mathcal{B}(D_s^+\to K_L^0K^+)}$
  = (-2.1±1.9±1.6)%, consistent with zero).
- $A_{CP}(D_s \to K_S K)$ = (0.6±2.8±0.6)% and $A_{CP}(D_s \to K_L K)$ = (-1.1±2.6±0.6)%

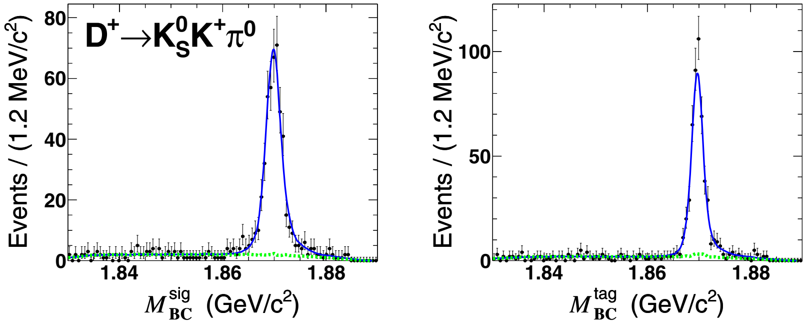
Published in PRD 99, 032002 (2019)

$D^+ \rightarrow K_{S/L}K$ (π^0) based on the 3773 data

- Also looked for similar final states, but in D^+ decays.
- Also added an additional π^0 (For this 3-body decay, MC was tuned based on $D \rightarrow KK\pi$ by CLEO : PRD 78, 072003 (2008)).







1sr measurements!

Consistent with zero

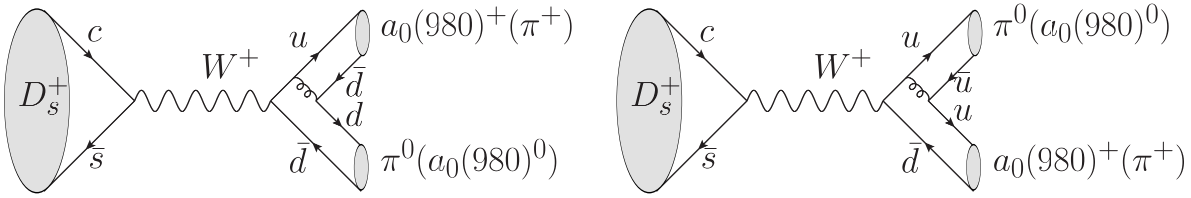
Signal mode	$\mathcal{B}(D^+)$ $(\times 10^{-3})$	$\mathcal{B}(D^-)$ $(\times 10^{-3})$	$\bar{\mathcal{B}}$ $(\times 10^{-3})$	$\mathcal{B}$ (PDG) $(\times 10^{-3})$	$\mathcal{A}_{CP}$ (%)
$K_S^0 K^\pm$	$2.96 \pm 0.11 \pm 0.08$	$3.07 \pm 0.12 \pm 0.08$	$3.02 \pm 0.09 \pm 0.08$	2.95 ± 0.15	$-1.8 \pm 2.7 \pm 1.6$
$K_S^0 K^\pm \pi^0$	$5.14 \pm 0.27 \pm 0.24$	$5.00 \pm 0.26 \pm 0.22$	$5.07 \pm 0.19 \pm 0.23$	$\cdots$	$1.4 \pm 3.7 \pm 2.4$
$K_L^0 K^\pm$	$3.07 \pm 0.14 \pm 0.10$	$3.34 \pm 0.15 \pm 0.11$	$3.21 \pm 0.11 \pm 0.11$	$\cdots$	$-4.2 \pm 3.2 \pm 1.2$
$K_L^0 K^\pm \pi^0$	$5.21 \pm 0.30 \pm 0.22$	$5.27 \pm 0.30 \pm 0.22$	$5.24 \pm 0.22 \pm 0.22$	$\cdots$	$-0.6 \pm 4.1 \pm 1.7$

Three-body decays

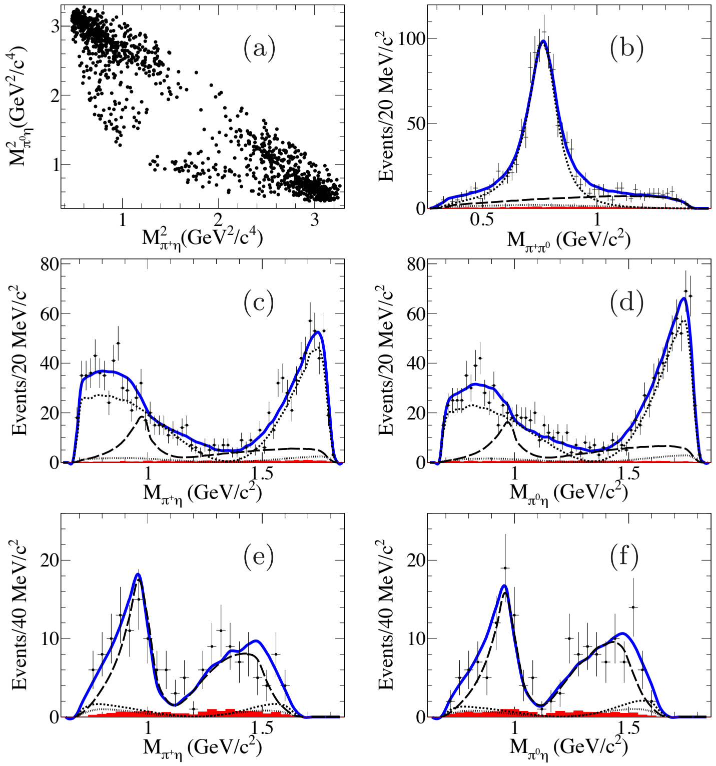
Submitted to PRL (arXiv:1903.04118)

$D_s^+ \to \pi^+\pi^0\eta$ based on the 4178 data

- Amplitude analysis based on DT-ed 1239 events (purity: 97.7%).
- W-annihilation dominant.



Amplitude	ϕ_n (rad)	FF_n
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	$0.783 \pm 0.050 \pm 0.021$
$D_s^+ \to (\pi^+\pi^0)_V\eta$	$0.612 \pm 0.172 \pm 0.342$	$0.054 \pm 0.021 \pm 0.025$
$D_s^+ \to a_0(980)\pi$	$2.794 \pm 0.087 \pm 0.044$	$0.232 \pm 0.023 \pm 0.033$



- Improved precision:

  $BF(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28 \pm 0.41)\%$

- First measurement (16.2σ stat. significance)!

  $BF(D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}, a_0(980)^{+(0)} \to \pi^{+(0)}\eta) = (1.46 \pm 0.15 \pm 0.23)\%$

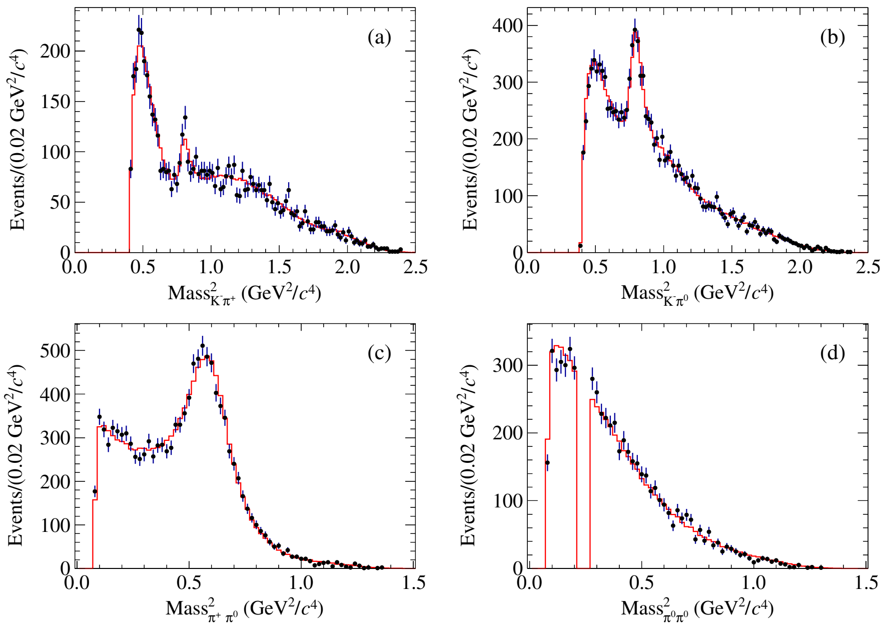
  Very large BF, compared to other W-annihilation decays

  (e.g., $D_s \to p\bar{n}/\omega\pi$ are all at 10^{-3} level).

Published in PRD 99, 092008 (2019)

$D^0 \rightarrow K^-\pi^+\pi^0\pi^0$ based on the 3773 data

- **Amplitude analysis based on DT-ed 5950 events (purity: 98.9%).**
- **One of the largest BF in the neutral D decays.**
  First amplitude analysis on this decay mode.



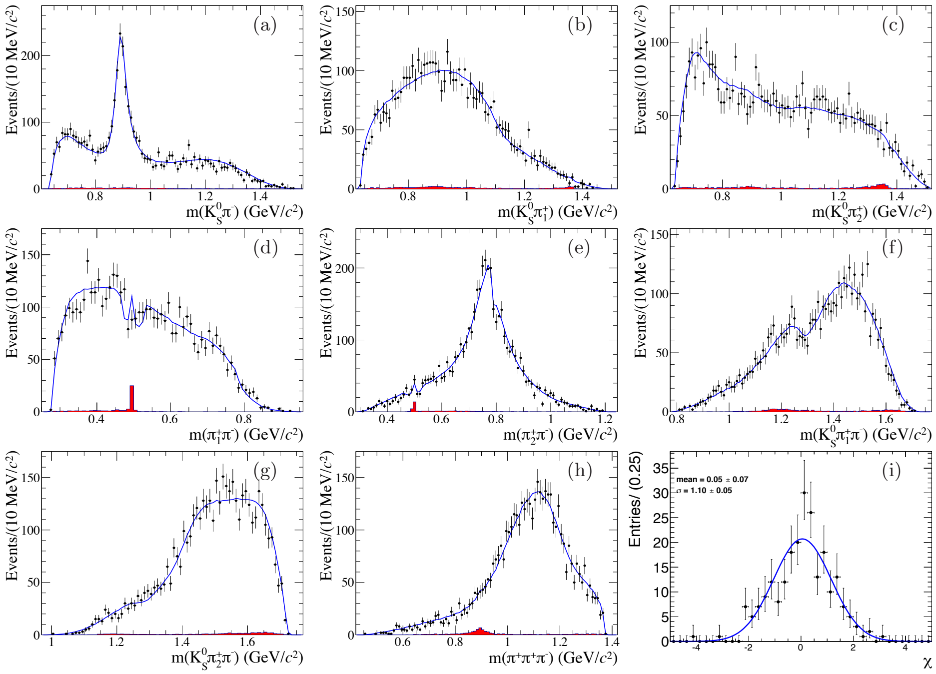
Amplitude mode	FF [%]	Phase [ϕ]	Significance [σ]
$D \rightarrow SS$			
$D \rightarrow (K^-\pi^+)_{S\text{-wave}}(\pi^0\pi^0)_S$	$6.92 \pm 1.44 \pm 2.86$	$-0.75 \pm 0.15 \pm 0.47$	>10
$D \rightarrow (K^-\pi^0)_{S\text{-wave}}(\pi^+\pi^0)_S$	$4.18 \pm 1.02 \pm 1.77$	$-2.90 \pm 0.19 \pm 0.47$	6.0
$D \rightarrow AP, A \rightarrow VP$			
$D \rightarrow K^-a_1(1260)^+, \rho^+\pi^0[S]$	$28.36 \pm 2.50 \pm 3.53$	0 (fixed)	>10
$D \rightarrow K^-a_1(1260)^+, \rho^+\pi^0[D]$	$0.68 \pm 0.29 \pm 0.30$	$-2.05 \pm 0.17 \pm 0.25$	6.1
$D \rightarrow K_1(1270)^-\pi^+, K^{*-}\pi^0[S]$	$0.15 \pm 0.09 \pm 0.15$	$1.84 \pm 0.34 \pm 0.43$	4.9
$D \rightarrow K_1(1270)^0\pi^0, K^{*0}\pi^0[S]$	$0.39 \pm 0.18 \pm 0.30$	$-1.55 \pm 0.20 \pm 0.26$	4.8
$D \rightarrow K_1(1270)^0\pi^0, K^{*0}\pi^0[D]$	$0.11 \pm 0.11 \pm 0.11$	$-1.35 \pm 0.43 \pm 0.48$	4.0
$D \rightarrow K_1(1270)^0\pi^0, K^-\rho^+[S]$	$2.71 \pm 0.38 \pm 0.29$	$-2.07 \pm 0.09 \pm 0.20$	>10
$D \rightarrow (K^{*-}\pi^0)_A\pi^+, K^{*-}\pi^0[S]$	$1.85 \pm 0.62 \pm 1.11$	$1.93 \pm 0.10 \pm 0.15$	7.8
$D \rightarrow (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[S]$	$3.13 \pm 0.45 \pm 0.58$	$0.44 \pm 0.12 \pm 0.21$	>10
$D \rightarrow (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[D]$	$0.46 \pm 0.17 \pm 0.29$	$-1.84 \pm 0.26 \pm 0.42$	5.9
$D \rightarrow (\rho^+K^-)_A\pi^0, K^-\rho^+[D]$	$0.75 \pm 0.40 \pm 0.60$	$0.64 \pm 0.36 \pm 0.53$	5.1
$D \rightarrow AP, A \rightarrow SP$			
$D \rightarrow ((K^-\pi^+)_{S\text{-wave}}\pi^0)_A\pi^0$	$1.99 \pm 1.08 \pm 1.55$	$-0.02 \pm 0.25 \pm 0.53$	7.0
$D \rightarrow VS$			
$D \rightarrow (K^-\pi^0)_{S\text{-wave}}\rho^+$	$14.63 \pm 1.70 \pm 2.41$	$-2.39 \pm 0.11 \pm 0.35$	>10
$D \rightarrow K^{*-}(\pi^+\pi^0)_S$	$0.80 \pm 0.38 \pm 0.26$	$1.59 \pm 0.19 \pm 0.24$	4.1
$D \rightarrow K^{*0}(\pi^0\pi^0)_S$	$0.12 \pm 0.12 \pm 0.12$	$1.45 \pm 0.48 \pm 0.51$	4.1
$D \rightarrow VP, V \rightarrow VP$			
$D \rightarrow (K^{*-}\pi^+)_V\pi^0$	$2.25 \pm 0.43 \pm 0.45$	$0.52 \pm 0.12 \pm 0.17$	>10
$D \rightarrow VV$			
$D \rightarrow K^{*-}\rho^+[S]$	$5.15 \pm 0.75 \pm 1.28$	$1.24 \pm 0.11 \pm 0.23$	>10
$D \rightarrow K^{*-}\rho^+[P]$	$3.25 \pm 0.55 \pm 0.41$	$-2.89 \pm 0.10 \pm 0.18$	>10
$D \rightarrow K^{*-}\rho^+[D]$	$10.90 \pm 1.53 \pm 2.36$	$2.41 \pm 0.08 \pm 0.16$	>10
$D \rightarrow (K^-\pi^0)_V\rho^+[P]$	$0.36 \pm 0.19 \pm 0.27$	$-0.94 \pm 0.19 \pm 0.28$	5.7
$D \rightarrow (K^-\pi^0)_V\rho^+[D]$	$2.13 \pm 0.56 \pm 0.92$	$-1.93 \pm 0.22 \pm 0.25$	>10
$D \rightarrow K^{*-}(\pi^+\pi^0)_V[D]$	$1.66 \pm 0.52 \pm 0.61$	$-1.17 \pm 0.20 \pm 0.39$	7.6
$D \rightarrow (K^-\pi^0)_V(\pi^+\pi^0)_V[S]$	$5.17 \pm 1.91 \pm 1.82$	$-1.74 \pm 0.20 \pm 0.31$	7.6
$D \rightarrow TS$			
$D \rightarrow (K^-\pi^+)_{S\text{-wave}}(\pi^0\pi^0)_T$	$0.30 \pm 0.21 \pm 0.30$	$-2.93 \pm 0.31 \pm 0.82$	5.8
$D \rightarrow (K^-\pi^0)_{S\text{-wave}}(\pi^+\pi^0)_T$	$0.14 \pm 0.12 \pm 0.10$	$2.23 \pm 0.38 \pm 0.65$	4.0
TOTAL	98.54		

- **Improved precision:**
  BF($D^0 \rightarrow K^-\pi^+\pi^0\pi^0$) = $(8.86 \pm 0.13 \pm 0.19)\%$
  led by $D^0 \rightarrow K^-a_1(1260)^+$.

Submitted to PRD (arXiv:1901.05936)

$D^+ \to K_S\pi^+\pi^+\pi^-$ based on the 3773 data

- Amplitude analysis based on DT-ed 4559 events (purity: 97.5%).
- Similar decay mode in the charged D decay.



Extracted BFs by the PDG BF($D^+ \to K_S\pi^+\pi^+\pi^-$)

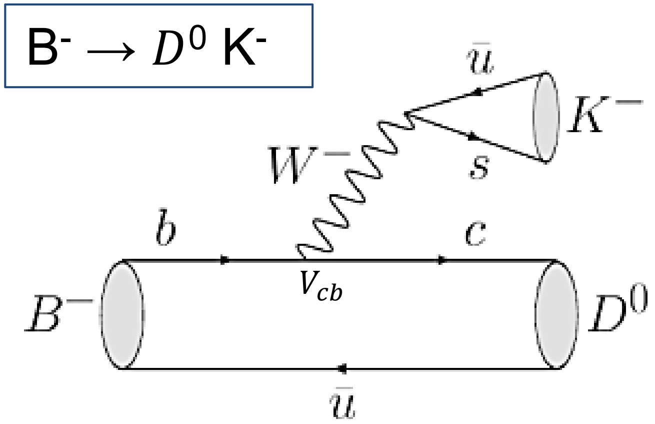
Component	Branching fraction (%)
$D^+ \to K_S^0 a_1(1260)^+(\rho^0\pi^+)$	$1.197 \pm 0.062 \pm 0.086 \pm 0.044$
$D^+ \to K_S^0 a_1(1260)^+(f_0(500)\pi^+)$	$0.163 \pm 0.021 \pm 0.005 \pm 0.006$
$D^+ \to \bar{K}_1(1400)^0(K^{*-}\pi^+)\pi^+$	$0.642 \pm 0.036 \pm 0.033 \pm 0.024$
$D^+ \to \bar{K}_1(1270)^0(K_S^0\rho^0)\pi^+$	$0.071 \pm 0.009 \pm 0.021 \pm 0.003$
$D^+ \to \bar{K}(1460)^0(K^{*-}\pi^+)\pi^+$	$0.202 \pm 0.018 \pm 0.006 \pm 0.007$
$D^+ \to \bar{K}(1460)^0(K_S^0\rho^0)\pi^+$	$0.024 \pm 0.006 \pm 0.015 \pm 0.009$
$D^+ \to \bar{K}_1(1650)^0(K^{*-}\pi^+)\pi^+$	$0.048 \pm 0.012 \pm 0.027 \pm 0.002$
$D^+ \to K_S^0\pi^+\rho^0$	$0.190 \pm 0.021 \pm 0.089 \pm 0.007$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$0.241 \pm 0.018 \pm 0.018 \pm 0.009$

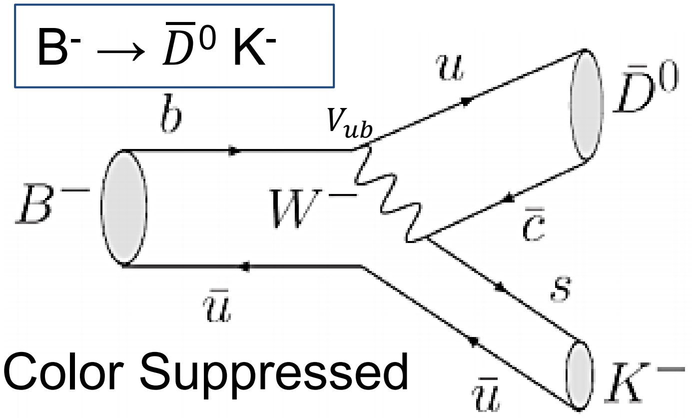
- Improved precisions.
- Consistent with the previous measurements.
- Again, led by $D^+ \to K_S a_1(1260)^+$
  (also consistent with our measurement in $D^0 \to K^-\pi^+\pi^+\pi^-$: PRD 95, 072010 (2017)).
- But $D^+ \to \bar{K}_1(1400)^0\pi^+$ is found to be larger, unlike what we saw in the two D^0 cases.

Preliminary result

$D^0 \to K_S\pi^+\pi^-$ based on the 3773 data

- To improve the measurement of the least known CKM angle, ϕ_3/γ

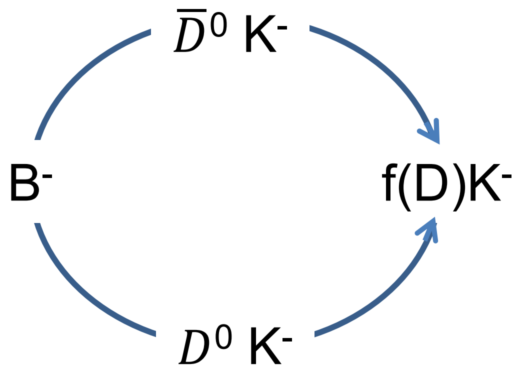

B- → D^0 K-


B- → $\bar{D}^0$ K-

Color Suppressed

$$\frac{\langle B^- \to \overline{D^0} K^-\rangle}{\langle B^- \to D^0 K^-\rangle} = r_B e^{i(\delta_B - \phi_3)}$$

Determine ϕ_3 through the measurement of
the interference between b →c and b →u transitions
when D^0 and $\overline{D}^0$ both decay to the same final state f(D).


$\bar{D}^0$ K-
B-
f(D)K-
D^0 K-

$D^0 \rightarrow K_S\pi^+\pi^-$

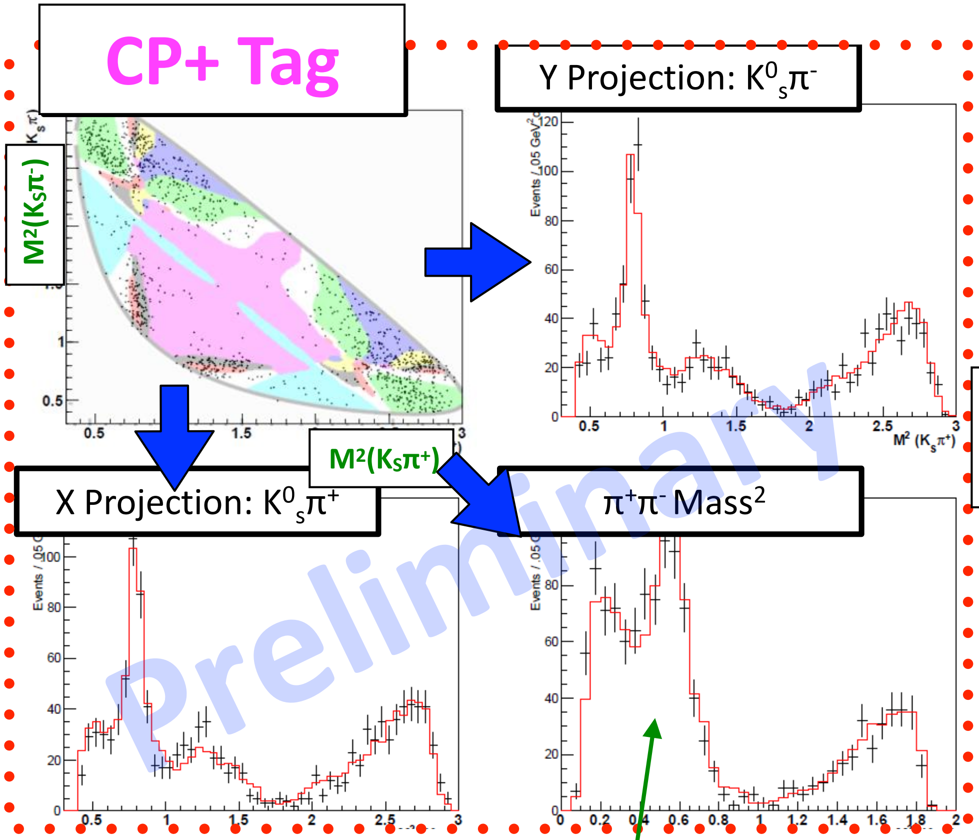
- ϕ_3/γ is measured at B-factories.
- They need the strong-phase difference between D and $\bar{D}$ to extract the total decay rate of B → D K.
- BESIII can provide it based on the quantum-correlated $D^0\bar{D}^0$-pair. ($e^+e^- \rightarrow \gamma^*$ ($\rightarrow \psi(3770)$) $\rightarrow D^0\bar{D}^0$)

- Efficiency-corrected yields in the ith Dalitz bin are; (see PRD82, 112006 (2010) for more details)
  - $\propto \pm c_i$ for DT: $D \rightarrow CP(\pm)$ states vs $D \rightarrow K_S\pi^+\pi^-$
  - $\propto c_i c_j + s_i s_j$ for DT (two Dalitz): $D \rightarrow K_S\pi^+\pi^-$ vs $D \rightarrow K_S\pi^+\pi^-$

c_i, s_i : weighted average of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ respectively where $\Delta\delta_D$ is the difference between phase of D^0 and $\overline{D}^0$

Preliminary result

For the case of "CP tag vs $K_S\pi^+\pi^-$"



CP+ Tag

$M^2(K_S\pi^-)$

Y Projection: $K^0_s\pi^-$

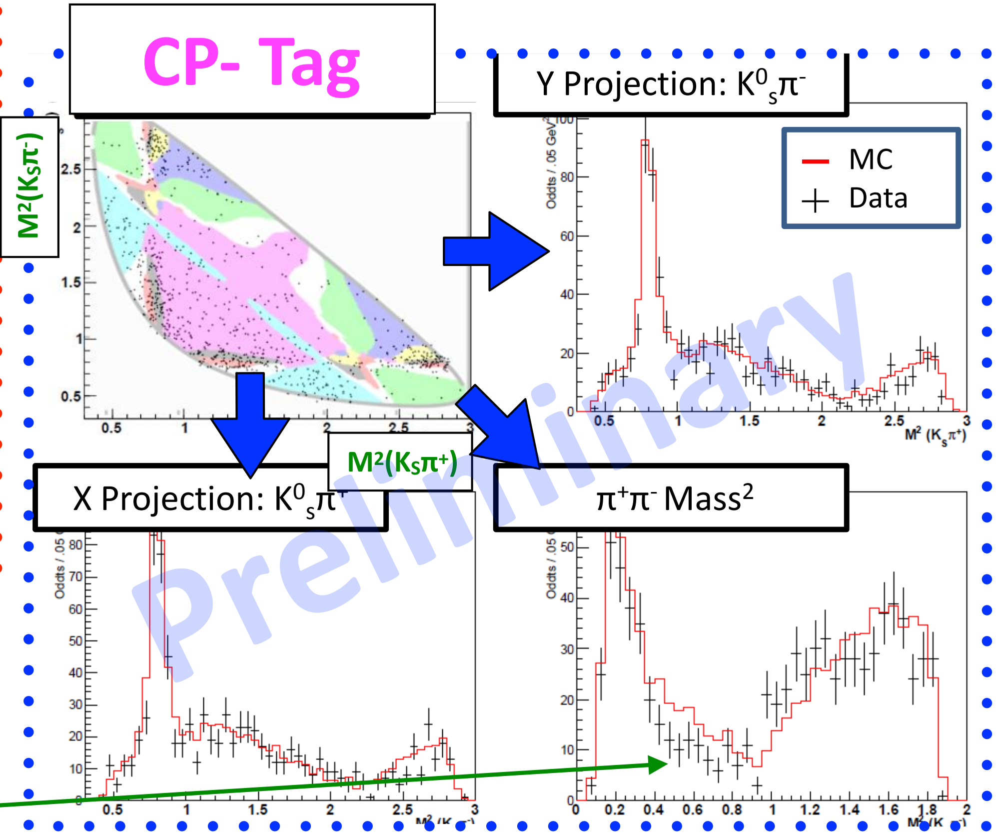
X Projection: $K^0_s\pi^+$

$M^2(K_S\pi^+)$

$\pi^+\pi^-$ Mass^2

CP Tag modes

Type	
CP+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$, $K_L\pi^0$
CP-	$K_S\pi^0$, $K_S\eta(\to\gamma\gamma)$, $K_S\eta(\to\pi^+\pi^-\pi^0)$, $K_S\omega$, $K_S\eta'$



CP- Tag

$M^2(K_S\pi^-)$

Y Projection: $K^0_s\pi^-$

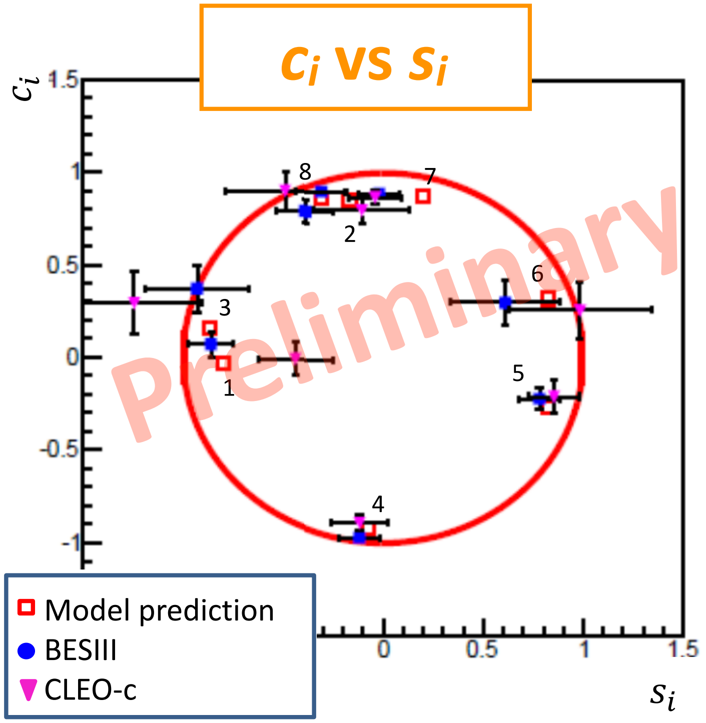
X Projection: $K^0_s\pi^+$

$M^2(K_S\pi^+)$

$\pi^+\pi^-$ Mass^2

Example of quantum-correlated D decay, $D^0 \to K_S\rho$!!

Results presented here will be using Optimal Binning scheme



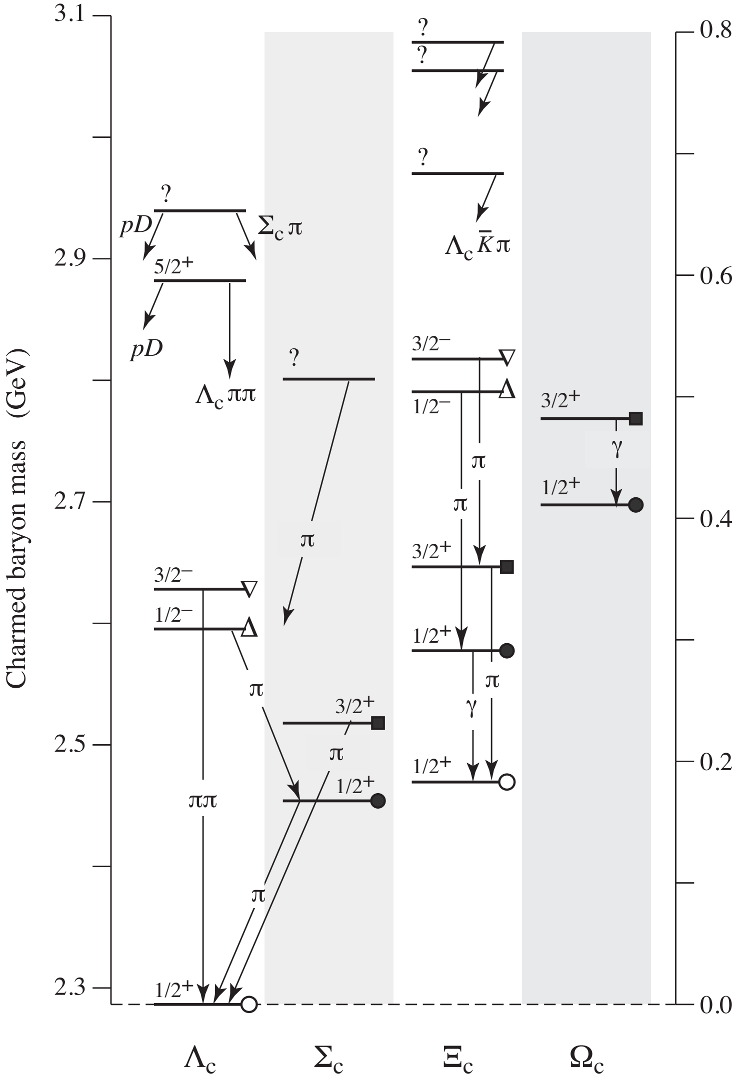
- **Based on BESIII 2.93fb^{-1} at E_{cm} = 3.773 GeV.**
- **Only statistical errors are shown.**
- **Consistent with the previous CLEO measurement.**

Runs	Collected / Expected integrated luminosity	Year attained	γ/ϕ_3 sensitivity
LHCb Run-1 [7, 8 TeV]	3 fb^{-1}	2012	8°
LHCb Run-2 [13 TeV]	6 fb^{-1}	2018	4°
Belle II Run	50 ab^{-1}	2025	1.5°
LHCb upgrade I [14 TeV]	50 fb^{-1}	2030	$< 1°$
LHCb upgrade II [14 TeV]	300 fb^{-1}	(>)2035	$< 0.4°$

- **Soon to be submitted.**
- **With the CLEO result, the uncertainty on ϕ₃/γ is found to be ~4° for LHCb. This will be improved to ~2.4° with this BESIII result. Currently working to add more tags, expect further reduction by ~×2.**
- **This would be sufficient precision until the era of Belle II and LHCb upgrades.**

Λ_c

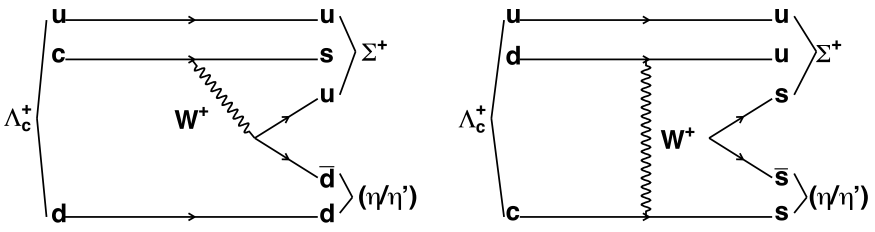
- The lightest charmed baryons
  → most of the charmed baryons will eventually decay into Λ_c. Important to know the decay properties of Λ_c.
- Also important input to Λ_b Physics as Λ_b decays dominantly to Λ_c.
- Total known measured BF is ~ 60%.



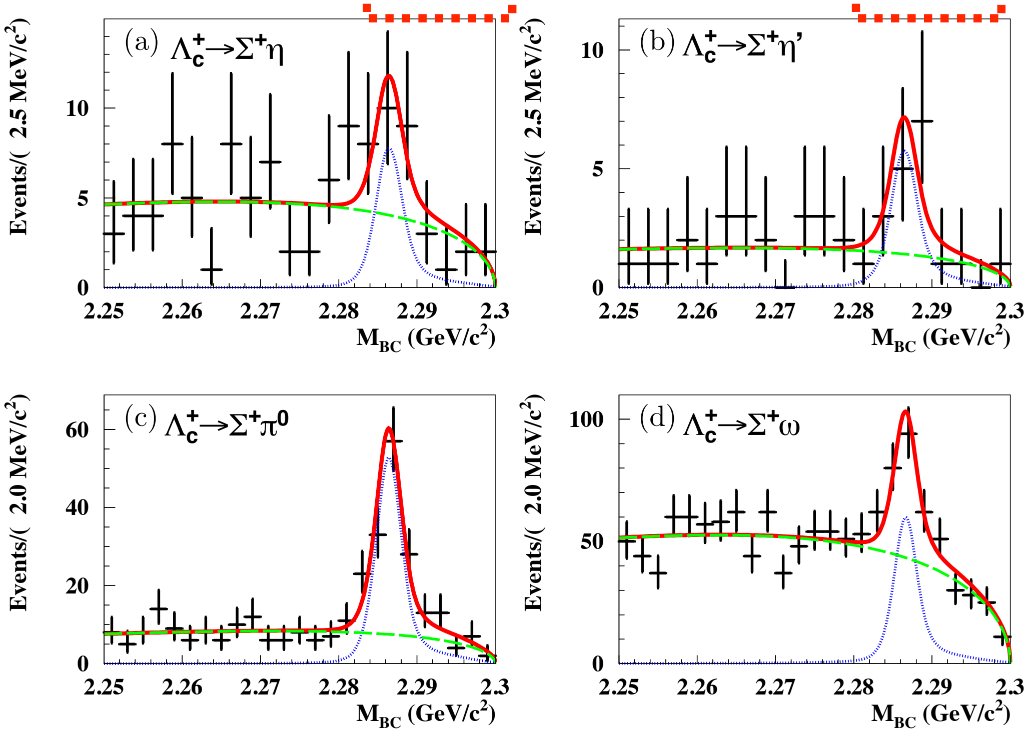
Published in CPC 43, 083002 (2019)

$\Lambda_c^+ \rightarrow \Sigma^+ (\eta/\eta')$ based on the 4600 data

- CF decays, proceed through nonfactorizable internal W-mission/exchange.
- Large range of predicted BFs.



- Measured:
  - BF($\Lambda_c^+ \rightarrow \Sigma^+\eta$)/BF($\Lambda_c^+ \rightarrow \Sigma^+\pi^0$) = 0.35±0.16±0.03 (<0.58 @90 C.L.)
  - BF($\Lambda_c^+ \rightarrow \Sigma^+\eta'$)/BF($\Lambda_c^+ \rightarrow \Sigma^+\omega$) = 0.86±0.34±0.07 (<1.20 @90 C.L.)



2.5σ

3.3σ

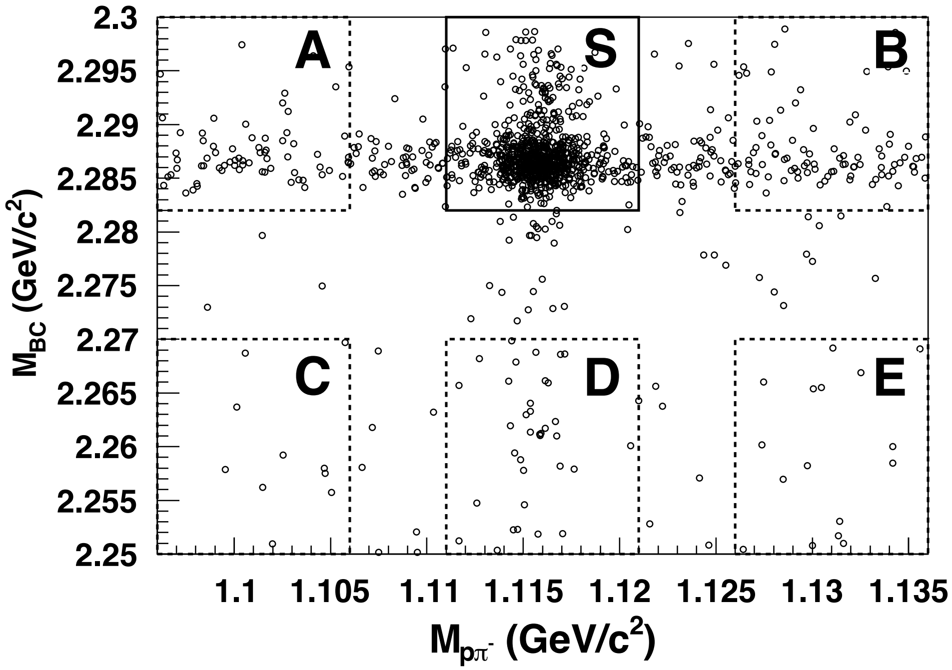
- With the known BF($\Lambda_c^+ \rightarrow \Sigma^+(\pi^0/\omega)$) from BESIII (PRL 116, 052001 (2016)): BFs in %.

Decay mode	Körner [5]	Sharma [3]	Zenczykowski [4]	Ivanov [6]	CLEO [12]	This work
$\Lambda_c^+ \rightarrow \Sigma^+\eta$	0.16	0.57	0.94	0.11	0.70±0.23	0.41±0.20 (<0.68)
$\Lambda_c^+ \rightarrow \Sigma^+\eta'$	1.28	0.10	0.12	0.12	-	1.34±0.57 (<1.9)

Published in PRL 121, 062003 (2018)

$\Lambda_c^+ \rightarrow \Lambda + X$

- Double tag method: Tagged with two modes; pKπ and pK_S.
- Extract yields from 2D distributions in bins of $p_{p\pi}$ and |cosθ|, where θ is the polar angle w.r.t. the beam pipe.



- $BF(\Lambda_c^+ \rightarrow \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$
- Also, looked for;

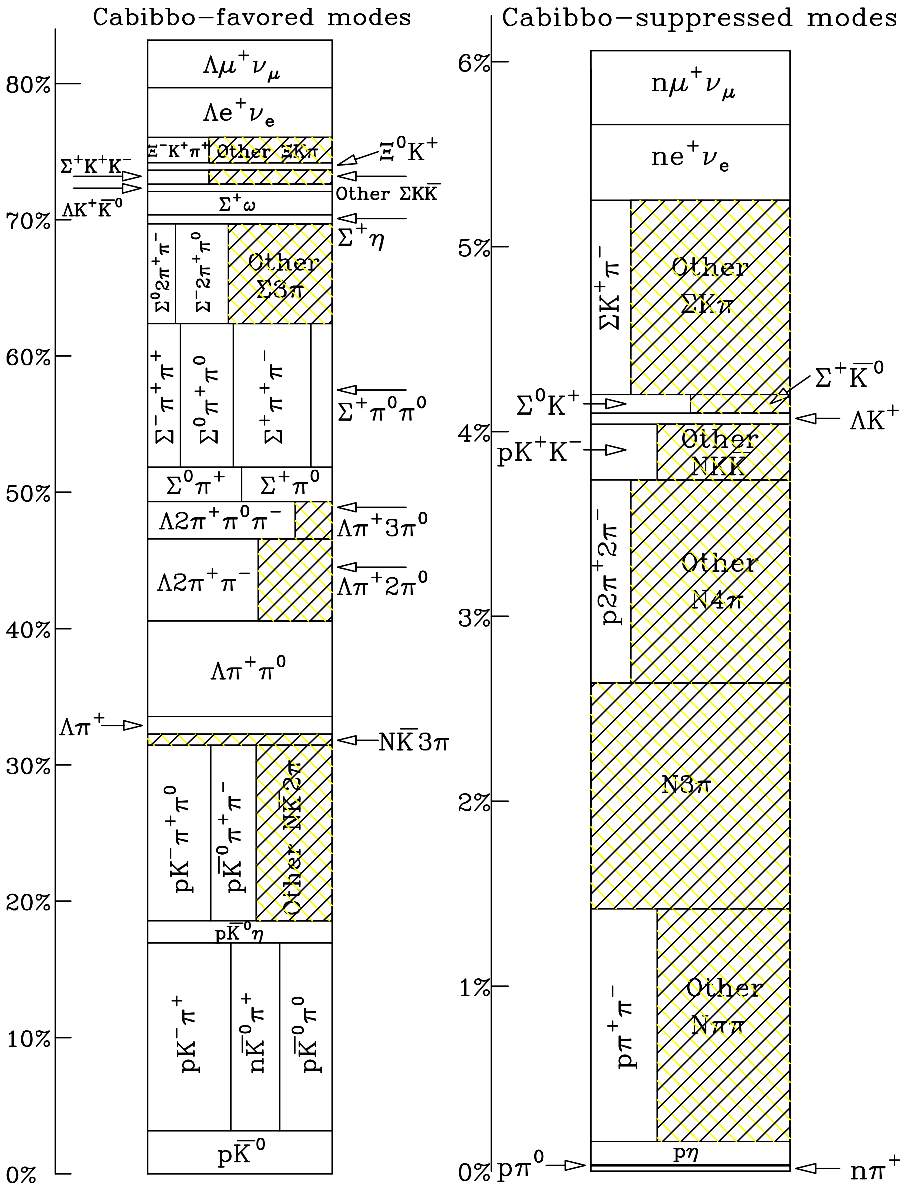
$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}.$$

- $A_{CP} = (+2.1^{+7.0}_{-6.6} \pm 1.4)\%$.

Mapping out Λ_c^+ decays

- Fig 1. from Gronau/Rosner/Wohl (PRD 98, 073003 (2018)).
- BFs represented by areas of boxes (no errors are shown).
- Shaded areas = not observed, yet, but expected by stat. isospin model (PRD 97, 116015 (2018)).

- SUM ~ 90±5%.
- What are the remaining?
  - should confirm those shaded ones.
  - should improve accuracies on those CS modes.
  - BESIII will take more data at E_{cm} = 4.6 GeV in the near future!



Summary

- Our results include new measurement,
  have confirmed and improved the precisions over the previous results.
- More measurements in $D_{(s)}$ hadronic decays are coming.
- Planning to take more data
  at/near $E_{cm} \sim 4.6$ GeV as well as $E_{cm} = 3.773$ GeV soon,
  which will allow us to even improve further precisions and rare/forbidden searches in $D_{(s)}/\Lambda_c$ decays.

- Other recent results not mentioned in in this report:
  - PRD 97, 052005 (2018) : SCD : $D^0 \to \omega\eta$, $\eta^{(\prime)}\pi^0$, and $\eta^{(\prime)}\eta$.
  - PRD 97, 072004 (2018) : $D \to PP$.
  - PRD 98, 092009 (2018) : $D^{0(+)} \to K_S\pi^{0(+)}\eta'$ and $D^0 \to K^-\pi^+\eta'$.
  - PLB 783, 200 (2018) : $\Lambda_c^+ \to \Xi^0 K^+$ and $\Xi(1530)^0 K^+$.
  - PRD 99, 032010 (2019) : $\Lambda_c^+ \to \Lambda\eta\pi^+$ and $\Sigma(1385)^+\eta$.
  - Submitted to PRD-RC (arXiv:1905.04707) : Weak decay asymmetric of $\Lambda_c^+ \to pK_S$, $\Lambda\pi^+$, $\Sigma^+\pi^0$, and $\Sigma^0\pi^+$.